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Analyses of historical solar eclipse records in Hokkaido Island in the 18–19th centuries

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Abstract

Solar eclipses have been recorded throughout history and across various ethnic groups. Their records have benefitted scientific discussions on multiple topics. These astronomical spectacles have also been recorded in the Japanese archipelago, but little has been known of the historical observations in the northern end: Hokkaido Island (known as Ezo Island until 1869). Here, we analysed three such early eclipse accounts from Hokkaido Island, both philologically and astronomically. We first analysed Tokunai Mogami's eclipse account written in 1786 January, which has been associated with the earliest eclipse record in Hokkaido Island. Our analysis showed that this eclipse was a deep partial solar eclipse outside the annular totality path of a hybrid eclipse, whereas it had previously been associated with an annular solar eclipse. This eclipse was also witnessed in the Ryukyu Kingdom, probably as a deep partial eclipse. We also located eclipse sketches in Kan'ichiro Mozume's diary and confirmed the local visibility of the annular eclipse in Otaru in 1872 June. We further analysed John Batchelor's eclipse folklore and identified the reported eclipse with a total solar eclipse in 1824 June. This folklore reported "tongues of fire and lightning" from the side of the "black dead sun." This description is morphologically consistent with that of solar coronal streamers around the solar minima. This eclipse is chronologically located around the minimum of Solar Cycles 6/7 and contrasts the Dalton Minimum with the Maunder Minimum, for which coronal streamers were reportedly missing, according to visual observations.

Key words: eclipses — history and philosophy of astronomy — Sun: corona — Sun: activity — time

1. Introduction

Total and annular solar eclipses have been observed and recorded throughout human history (De Jong & Van Soldt 1989; Stephenson 1997; Tanikawa et al. 2010; Pasachoff & Olson 2014; Pasachoff 2017). These observations have been augmented in astrophysical discussions on

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multiple topics such as solar coronal variability (Loucif and Koutchmy 1989; Pasachoff 2017; Hayakawa et al. 2020), radio astronomy (Orchiston 2004), and solar–terrestrial interactions (Harrison & Hanna 2016). Total and annular solar eclipses require exact coincidences of the solar and lunar disks and form only narrow totality/annularity paths, whereas partial eclipses are still visible around these paths. Consequently, such eclipse records are occasionally complemented in discussions and reconstructions of scientific history (Saito 1969; Orchiston & Orchiston 2021; Orchiston et al. 2021), historical chronologies (Martin & Skidmore 2012; Morrison et al. 2019; Hayakawa et al. 2021b), and variations of Earth's rotation (Stephenson 1997; Tanikawa et al. 2010; Orchiston et al. 2015; Sôma & Tanikawa 2015; Martínez Usó et al. 2016; Stephenson et al. 2016; Morrison et al. 2021; Hayakawa et al. 2022). Solar eclipses have also occasionally been recorded in folklore and arts without exact dates. These accounts have subsequently been subjected to scientific analyses (Hamacher & Norris 2011; Pasachoff & Olson 2014; Vaquero & McKim Malville 2014; Fuller & Hamacher 2017; Goto 2021).

Historically, solar eclipses have been widely reported in the Japanese archipelago in chronicles and diaries from 628 April onward (e.g., Kanda 1935; Tanikawa & Sôma 2004). Among them, the total eclipse in 1887 August formed a benchmark for the modern Japanese astronomy, attracting not only professional Japanese scientists but also non-professional citizens and foreign eclipse expeditions (e.g., Shiiya 1888; Todd 1888; Arai 1890; Saito 1969). This solar eclipse was observed all over Japan and was recorded in the earliest photograph of a solar eclipse and solar corona in Japanese observational history (Arai 1890).

This solar eclipse was also observed in Hokkaido, Island, as described in John Batchelor's report (Batchelor 1887). However, little is known about the solar eclipse observations made prior to the occurrence of this eclipse in Hokkaido Island, the northernmost great island in the Japanese archipelago. This island was known as Ezo Island until 1869. Hereafter, for convenience, we call this island Hokkaido Island throughout this article. With respect to Hokkaido Island, it is Tokunai Mogami's account of a solar eclipse that is most widely known to the scientific community. This event has been interpreted as an annular solar eclipse that occurred on 1786 January 30 and the earliest datable report of a solar eclipse in Hokkaido Island (Sueoka 2009).

Recent research progress in the analysis of the Earth's rotation (Stephenson et al. 2016; Morrison et al. 2021) has enabled the computation of the most probable visibility conditions for the past solar eclipses and the evaluation of their reliability, authenticity, and provenance, as shown in several case studies (Morrison et al. 2019; Morrison & Stephenson 2020; Stephenson et al. 2020; Hayakawa et al. 2021b). Therefore, this study aims at extending archival investigations and astronomical analyses of the early solar eclipses witnessed in Hokkaido prior to Batchelor's observation of the solar eclipse in 1887 (Batchelor 1887). This article located three eclipse records and focused the analyses on these accounts: Tokunai Mogami's account in 1786 (Otomo 1943), Kan'ichiro Mozume's account in 1872, and John Batchelor's undated folklore account (Batchelor 1887). We also identified the solar eclipse described in Batchelor's folklore on the basis of these eclipse records and assessed the scientific implications of their descriptions.

2. Method

For these historical eclipses in Hokkaido, we computed the relative positions of the Sun and the Moon against Earth and have given observational sites, according to the JPL (Jet Propulsion Laboratory) ephemerides DE431 (Folkner et al. 2014). We applied the latest parameter for the Earth's rotation rate (ΔT; difference between terrestrial time and universal time) and geographically corrected the totality/annularity paths, following the latest ΔT reconstruction (Stephenson et al. 2016; Morrison et al. 2021). To calculate geographical limits of total/annular eclipse zones and local predictions of solar eclipses, we followed the procedures given in the Explanatory Supplement from H. M. Nautical Almanac Office (1961). We have then identified the most probable observational sites from the documentations to compute the maximum magnitudes and compare the positions against our calculations for the totality/annularity paths of these eclipses. From here on, we abbreviate local mean time and local apparent time as LMT and LAT, respectively.

Here, we check the robustness of our method with two case reports for the timed solar eclipses. First, we analysed a case report of the total eclipse in 1887 August. As stated above, this eclipse was reported from all over Japan. Apart from Plate V of Arai (1890), we located one of the copies of Arai and Sugiyama's eclipse photographs for this total solar eclipse (figure 1) in the Paris Observatory (Inv.I.1426). This eclipse photograph is considered one of the earliest eclipse/corona photograph series in Japanese history (e.g., Arai 1890). Here, this eclipse photograph explicitly shows their observations of a total solar eclipse at Yomeiji-yama in Japan (N37°37′, E138°59′) on 1887 August 19 with three time stamps: $15^{h}40^{m}36^{s}.5$, $15^{h}41^{m}25^{s}.4$, and $15^{h}42^{m}06^{s}.2$ LMT; the descriptions for the photograph indicate that the totality began at $15^{h}39^{m}28^{s}$ LMT and ended at $15^{h}42^{m}40^{s}$ LMT. Our calculation locates the local beginning and end of this total eclipse as $15^{h}39^{m}23^{s}$ LMT and $15^{h}42^{m}41^{s}$ LMT, respectively. The differences of 1–5 s in the contact times between their observations and our calculations can

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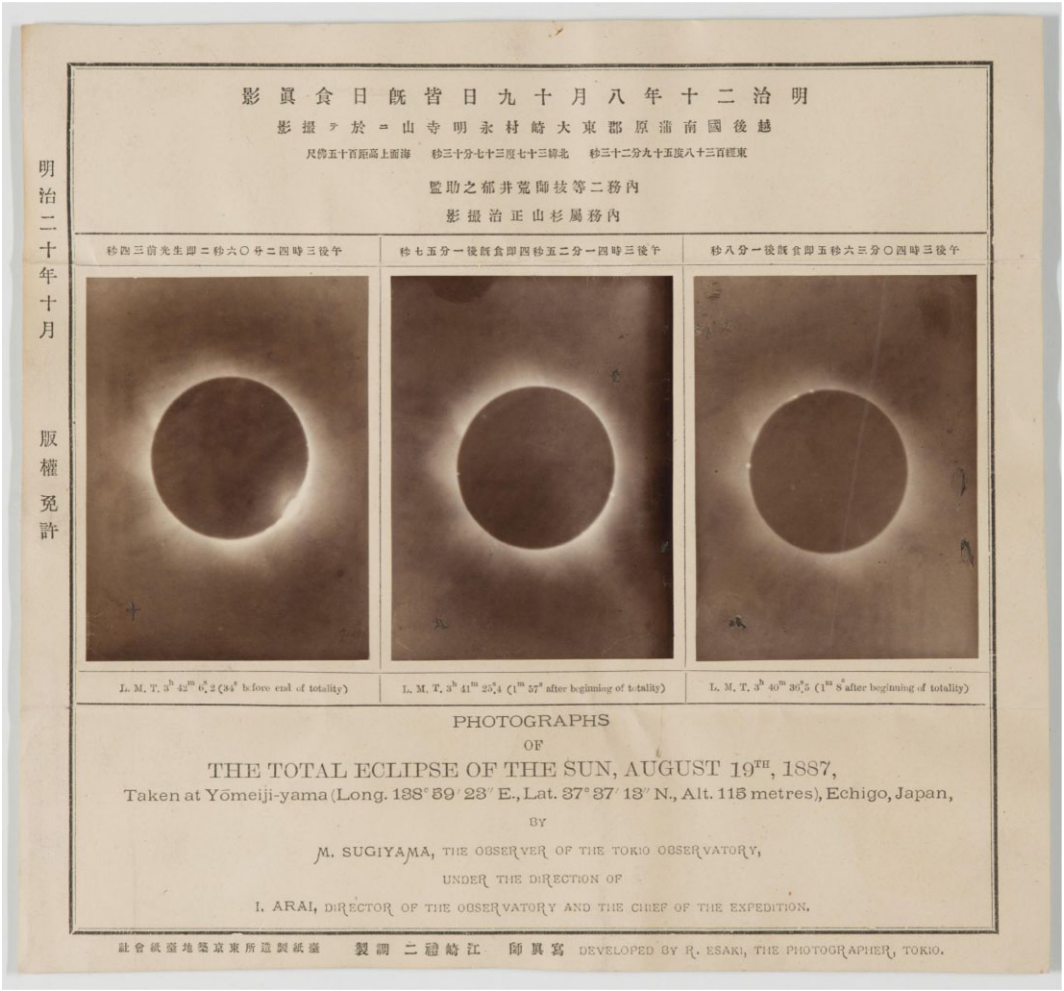
明治二十年十月
版權免許
明治二十年八月十九日皆既日食眞影
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L. M. T. 3h 42m 6s.2 (34s before end of totality)
L. M. T. 3h 41m 25s.4 (1m 57s after beginning of totality)
L. M. T. 3h 40m 36s.5 (1m 8s after beginning of totality)
PHOTOGRAPHS
OF
THE TOTAL ECLIPSE OF THE SUN, AUGUST 19TH, 1887,
Taken at Yōmeiji-yama (Long. 138° 59′ 23″ E., Lat. 37° 37′ 13″ N., Alt. 115 metres), Echigo, Japan,
BY
M. SUGIYAMA, THE OBSERVER OF THE TOKIO OBSERVATORY,
UNDER THE DIRECTION OF
I. ARAI, DIRECTOR OF THE OBSERVATORY AND THE CHIEF OF THE EXPEDITION.
製圖調二 江崎穩 寫眞師 DEVELOPED BY R. ESAKI, THE PHOTOGRAPHER, TOKIO.
東京築地活版製造所寫眞紙部

Fig. 1. Ikunosuke Arai and Masaharu Sugiyama's eclipse photographs taken at Yomeiji-yama in Japan (N37°37′, E138°59′) on 1887 August 19, reproduced with courtesy of L'observatoire de Paris (Inv.I.1426). This photograph has been considered to be the earliest photograph of the solar eclipse and solar corona in Japan [see also: Plate V of Arai (1890)].

be attributed to errors in their observation times and their station coordinates and to the effect of the lunar limb irregularities. These details confirm the reliability of their observations and the robustness of our eclipse calculation method.

Secondly, we analysed a case report for the total solar eclipse in 1778 June. This eclipse is known for visual accounts of solar coronal streamers in D'Ulloa and Desoteux (Vaquero 2003). Here, we have consulted their source records (Le Monnier 1781) and shown their coloured eclipse drawings in figure 2. Among these observers, Desoteux witnessed the total solar eclipse at Salé around "$4^{h}27^{m}2^{s}.5$" (Le Monnier 1781, p. 63). Here, we located the geographical coordinate of Salé (N34°03′, W6°49′) and computed the local beginning, maximum, and end of this total eclipse as $16^{h}26^{m}46^{s}$ LMT ($16^{h}24^{m}52^{s}$ LAT), $16^{h}28^{m}30^{s}$ LMT ($16^{h}26^{m}36^{s}$ LAT), and $16^{h}30^{m}14^{s}$ LMT ($16^{h}28^{m}20^{s}$ LAT), respectively. Our calculation looks consistent with the report, whereas the clock accuracy matters for their details here (e.g., figure 10 of Stephenson et al. 2016).

3. Analyses of Tokunai Mogami's eclipse report on 1786 January 30

The earliest datable solar eclipse observed in Hokkaido has been identified with what Tokunai Mogami (最上徳内: 1755–1836) reported in 1786 (Sueoka 2009). He was a Japanese technical bureaucrat and explorer. He had studied Japanese mathematics, astronomy, land survey, and economy until then. He had participated in Japanese expeditions to Hokkaido Island, the southern Kuril Islands, and Sakhalin Island in 1785–1792. He visited Mitsuishi, Hokkaido, in 1786 and met a local merchant, Denkichi Abeya, who witnessed the solar eclipse on 1786 January 30 (figure 3, left; Otomo 1943). He recollected his conversation with Denkichi in "Ezo Soshi" as follows:

> In the daytime of the New Year's Day (i.e., 1786 January 30), the sky suddenly became cloudy to be like darkness. Because of this, the Ezo people (i.e., the Ainu) made uproar and screamed battle cries *utake* very hard (figure 3, left; Otomo 1972).

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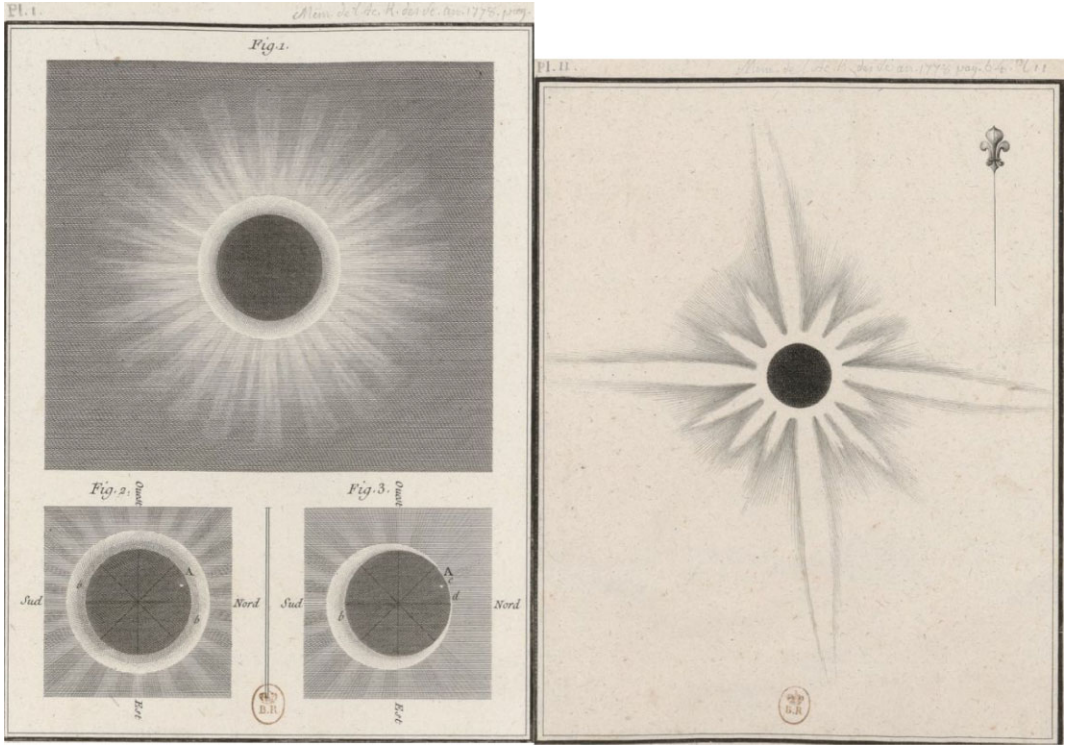

Fig. 2. Graphical records for total solar eclipse on 1778 June 24, as reproduced from Plates I and II of Le Monnier (1781) (spurce Gallica/Bibliothèque nationale de France). The left- and the right-hand panels show eclipse drawings of D'Ulloa on the Atlantic Ocean and Desoteux at Salé (see also Vaquero 2003).

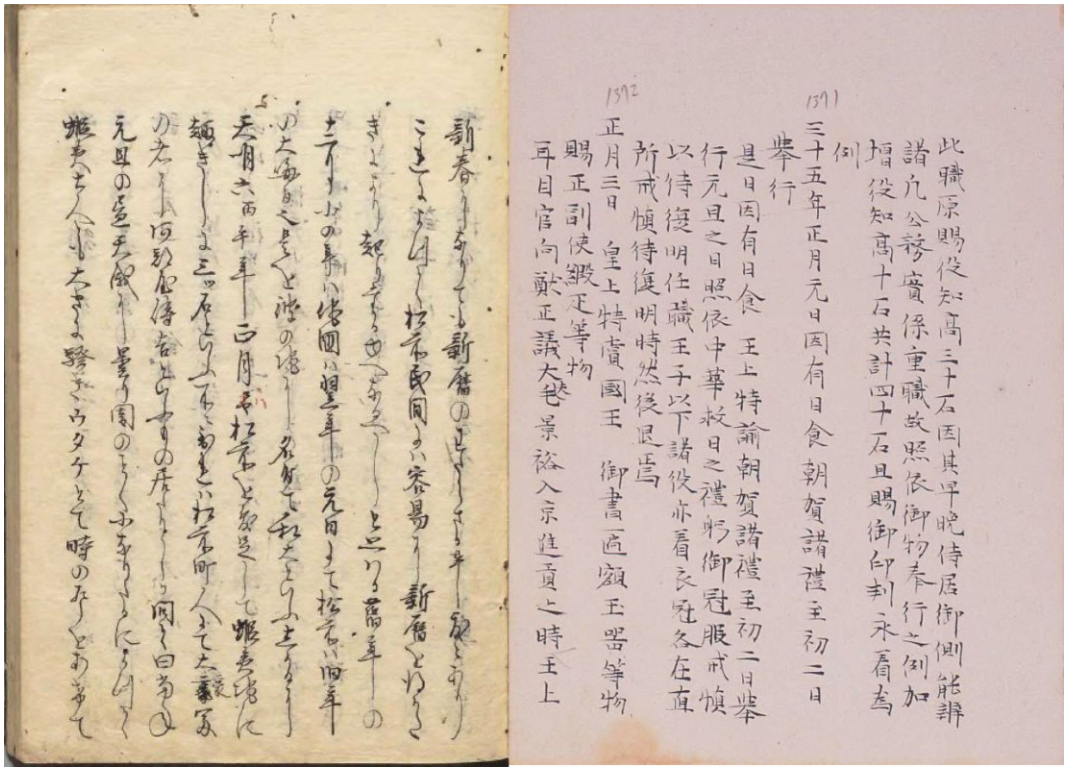

Fig. 3. Historical accounts of the solar eclipse on 1786 January 30. Left: Excerpt of Tokunai Mogami's account of the solar eclipse in "Ezo Soshi", reproduced from MS 178–0209 (f. 9a) © the National Archives of Japan (CC BY 4.0). Right: Excerpt of Kyuyo's account of the solar eclipse, reproduced from MS 1285 (v. 17, f. 2a) © the Okinawa Prefectural Library (CC BY 4.0).

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Fig. 4. Comparison of the Mitsuishi and Shuri observations of the totality paths of the solar eclipse on 1786 January 30.

This eclipse report had been associated with an "annular solar eclipse" which "started from the southern Taiwan, coming across the eastern Hokkaido, and headed northward along Kuril Islands" and "embraced the Ainu Moshiri (i.e., Hokkaido) in the black shade" in Sueoka (2009). However, our calculations slightly modify the existing interpretation, based on the latest ΔT value (21 s) in 1786 (Stephenson et al. 2016; Morrison et al. 2021). First, this eclipse was not a simple annular eclipse but rather a hybrid eclipse, which was manifested as a total solar eclipse from the southern Taiwan to the eastern Honshu Island and as an annular solar eclipse from the eastern Honshu Island further northward (figure 4). Secondly, Mitsuishi (N42°15′, E142°33′) was outside the annularity path. The eclipse magnitude reached only 0.96 at $03^{h}36^{m}02^{s}$ UT, namely, at $12^{h}52^{m}27^{s}$ LAT, as shown in the left panel of figure 5. It is somewhat unrealistic to think that Denkichi has witnessed the annular solar eclipse, as he would have had to travel southward or eastward over the Pacific Ocean or the ΔT would have had to have significantly drifted ($-694\,\mathrm{s} < \Delta T < -666$ s), in contrast with the existing ΔT value (21 ± 1 s) for 1786 (Stephenson et al. 2016). However, an eclipse of this magnitude could have significantly reduced the sky brightness, as indicated by measurements of an annular solar eclipse on 2012 May 21 [figure 11 of Ohgoe (2012)], which yielded a calculated maximum magnitude of 0.97. Therefore, the event cited in Mogami's report was probably a deep partial solar eclipse outside the annularity path of the hybrid solar eclipse on 1786 January 30.

Interestingly, this eclipse was also reported to have been observed in the Ryukyu Kingdom (modern Okinawa Island) on the same date (Kanda & Ohsaki 1932, p. 222). Kyuyo (球陽), Ryukyu Kingdom's official history, states: "In the 35th year (i.e., King Sho Boku's reign), New Year's date (i.e., 1786 January 30), as there was a solar eclipse, the Choga rituals were carried out on the 2nd day" (figure 3, right; Kyuyo Kenkyukai 1974a, 1974b). At that time, King Sho Boku (reign 1752–1794) resided at Shuri (N26°13′, E127°43′). Our calculation indicates that Shuri was slightly out of the totality path, as this was a hybrid eclipse, switching from a totality path to an annularity path in the eastern Japan. The eclipse magnitude reached only 0.99 at $02^{h}51^{m}53^{s}$ UT, namely, at $11^{h}08^{m}59^{s}$ LAT (figure 5, right). This is a unique early case of simultaneous eclipse observations on both Hokkaido and Okinawa Islands. This eclipse did not reach totality in either of these cases.

4. Analyses of Kan'ichiro Mozume's eclipse sketches on 1872 June 6

Further, Hokkaido hosted an annularity eclipse in 1872 June, but the scientific community had to-date acquired no reports for this solar eclipse so far and has tentatively explained the observational difficulty with the high solar altitude during this annular solar eclipse (Ohgoe 2009). However, we have recently located four eclipse sketches in Mozume Nisshi, Kan'ichiro Mozume's diary held by the Board of Education in Tobetsu (figure 6). Kan'ichiro Mozume (鵙目貫一郎: 1840–1877) was one of the servants of the Miyagi Fief and studied at Shoheizaka Gakumonjo (昌平坂学問所), a Japanese Shogunate school. He was relocated in Hokkaido Island after the Meiji Revolution and started a private school in Otaru from 1871. He recorded his daily life in Otaru on Tenkai Nikki, including this solar eclipse. This eclipse account reads as follows:

> From 4th *toki* and 6th *bu*, when the solar eclipse started from upper right, it looked like this (a). At 9th *toki* and 3rd *bu*, when it had a great magnitude, it looked like this (b). After a while, it looked like this (c). At 9th *toki* 9th *bu*, when it ended, it looked like this (d). At the onset of the eclipse, grasses, woods, and soil were illuminated in yellow. When it had a great magnitude, the solar disk was slightly shiny, as bright as the full moon. It finally got back to normalcy. The solar disk rotated continuously and it was difficult to gaze at it (the Board of Education in Tobetsu, MS Ayuta 0607, v. 1, f. 44a).

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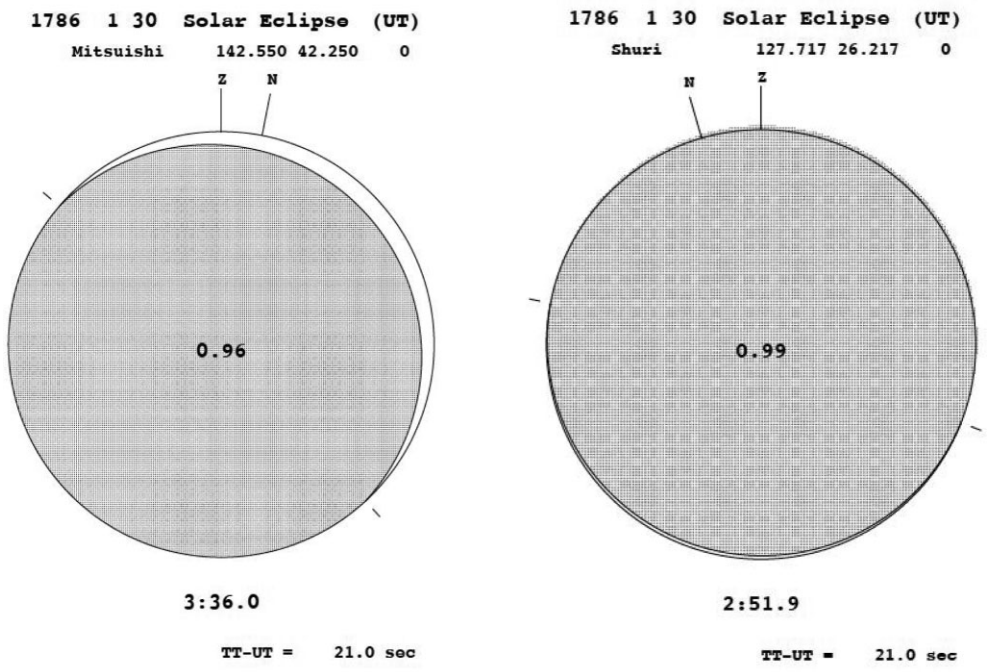

Fig. 5. Maximum eclipse magnitudes at Mitsuishi (left) and Shuri (right) on 1786 January 30.

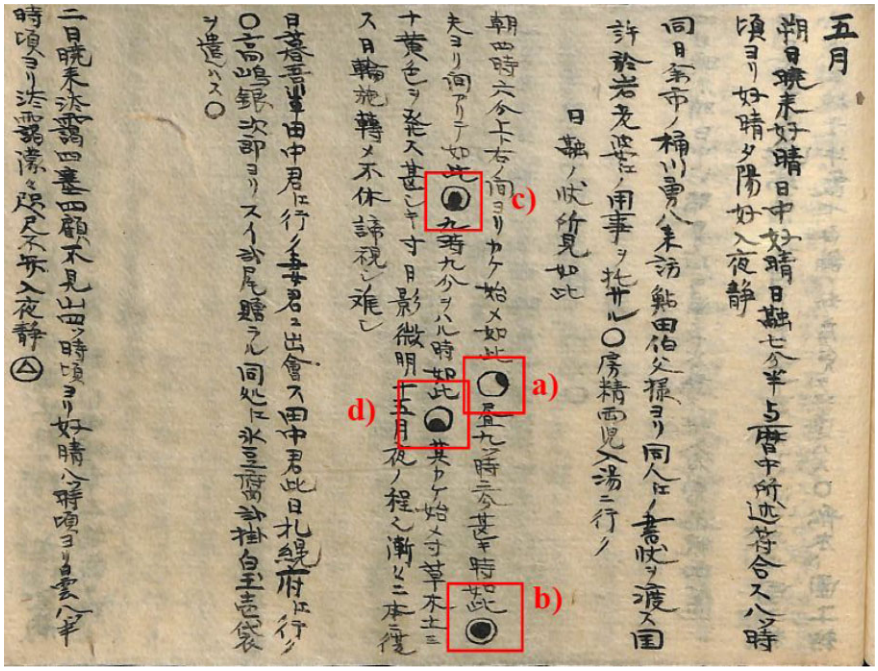

Fig. 6. Kan'ichiro Mozume's eclipse drawings reproduced from his autograph manuscript of Tenkai Nikki (MS Ayuta 0607, v. 1, f. 44a) © the Board of Education in Tobetsu.

Here, Kan'ichiro Mozume evidently depicted an annular eclipse visibility upon the maximum and partial eclipse visibility around this. It is known that Kan'ichiro Mozume resided in Otaru (N43°11′, E141°00′) from 1871 (Yamamoto & Ishikawa 2022, p. 20). This is consistent with our astronomical calculations for the eclipse visibility in Otaru based on the latest ΔT value (0.2 s) in 1872 (Stephenson et al. 2016; Morrison et al. 2021), which locate Otaru in the annularity path (figure 7) and confirm eclipse visibility in $11^{h}42^{m}43^{s}$–$15^{h}00^{m}31^{s}$ LAT, annular

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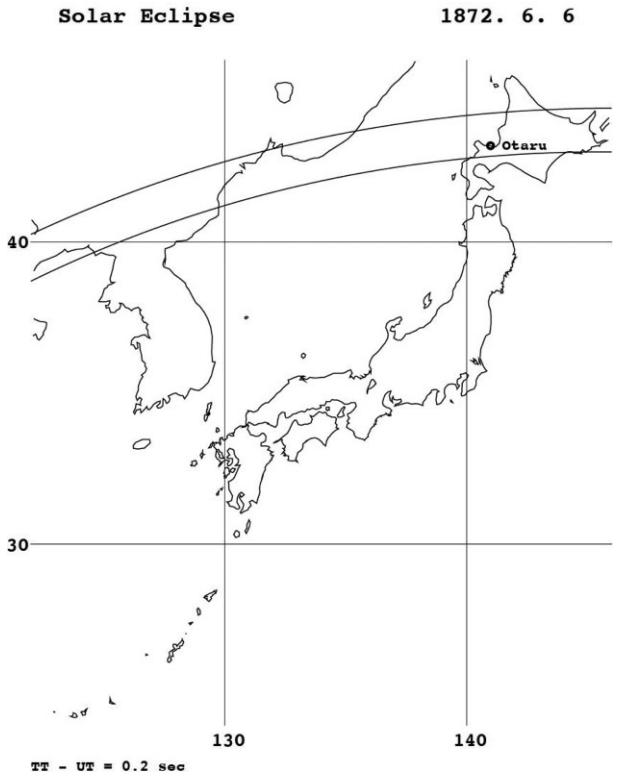

Fig. 7. Relative locations of Otaru and our annularity path of the solar eclipse on 1872 June 6.

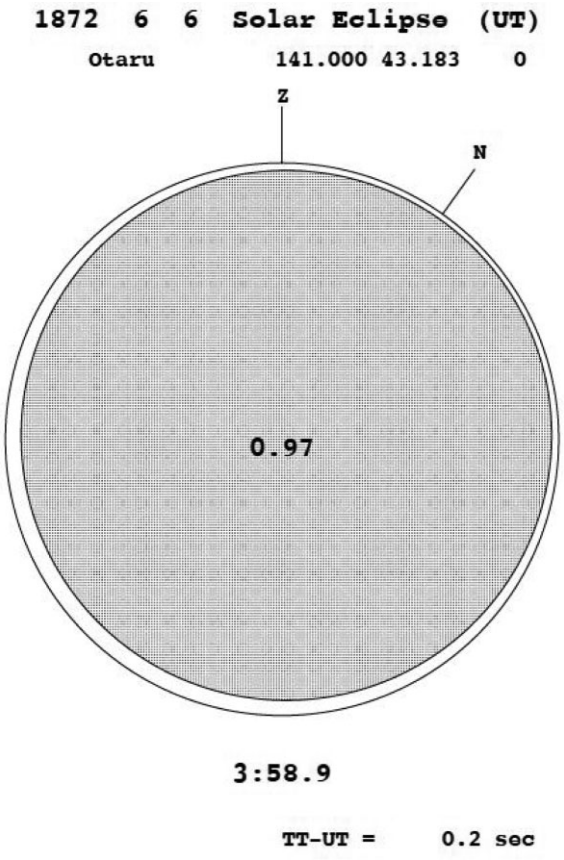

Fig. 8. Maximum eclipse magnitude at Otaru on 1872 June 6.

eclipse visibility in $13^{h}22^{m}44^{s}$–$13^{h}26^{m}23^{s}$ LAT, and maximal eclipse magnitude of 0.97 at $13^{h}24^{m}33^{s}$ LAT (figure 8). The observational time looks consistent with the temporal hour system at that time, as the local sunrise and local sunset were at $04^{h}22^{m}$ LAT and $19^{h}38^{m}$ LAT, the dawn and dusk were at $03^{h}38^{m}$ LAT and $20^{h}23^{m}$ LAT, and therefore the 9th toki was from $12^{h}00\overset{m}{.}5$ LAT to $14^{h}48^{m}$ LAT. Note that the dawn and dusk at that time were defined as the times when the Sun's altitude was at $7^{\circ}21'40''$ below the horizon, and 1 toki during daytime was determined by dividing the time from the dawn to the dusk by 6 so that the 9th toki turns out to be from $12^{h}00\overset{m}{.}5$ LAT to $14^{h}48^{m}$ LAT on 1872 June 6 in Otaru. This unique eclipse record has filled the data gap that existed for the Japanese eclipse observation in 1872.

5. Identification and analyses of John Bachelor's folklore eclipse

On his eclipse observation in 1887 August, John Batchelor recorded an Ainu folklore for a total solar eclipse (Batchelor 1887). John Batchelor (1855–1944) was an Anglican missionary to the Ainu in Hokkaido and witnessed a solar eclipse on 1887 August 19. Batchelor determined the upcoming eclipse date using an almanac and prepared blackened glasses for his eclipse observation. Although he was outside the totality path (cf. Todd 1888), he still managed to show the partial eclipse to the Ainu through the blackened glasses and reported their fears on the "dying" sun and their relevant folklore (Batchelor 1887, p. 228). He cited the following folklore account of a total solar eclipse witnessed by one of their ancestors:

> Sober Ainu traditions of eclipses are all of one stamp, and run thus: "When my father was a child he heard his old grandfather say that his grandfather saw a total eclipse of the sun. The earth became quite dark, and shadows could not be seen; the birds went to roost, and the dogs began to howl. The black dead sun shot out tongues of fire and lightning from its sides, and the stars shone brightly. Then the sun began to return to life, and the faces of the people wore an aspect of death; and as the sun gradually came to life, then men began to live again" (Batchelor 1887, p. 228).

This account itself does not allow us to determine immediately where and when this total eclipse occurred, as none of this information was explicitly clarified (Batchelor 1887). However, Batchelor reported this folklore immediately after his descriptions of the Ainu reactions to the solar eclipse on 1887 August 19. Batchelor probably acquired this folklore about this eclipse. Batchelor's autobiography

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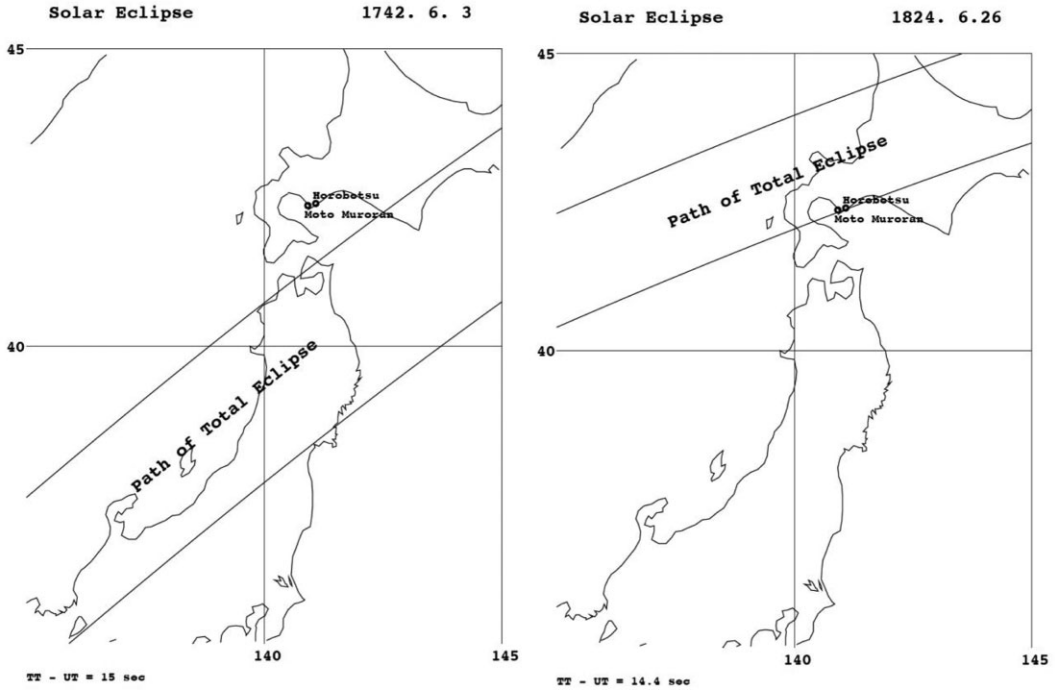

Fig. 9. Geographical visualisations of the totality paths of solar eclipses on 1742 June 3 and 1824 June 26, for Horobetsu and Moto Muroran.

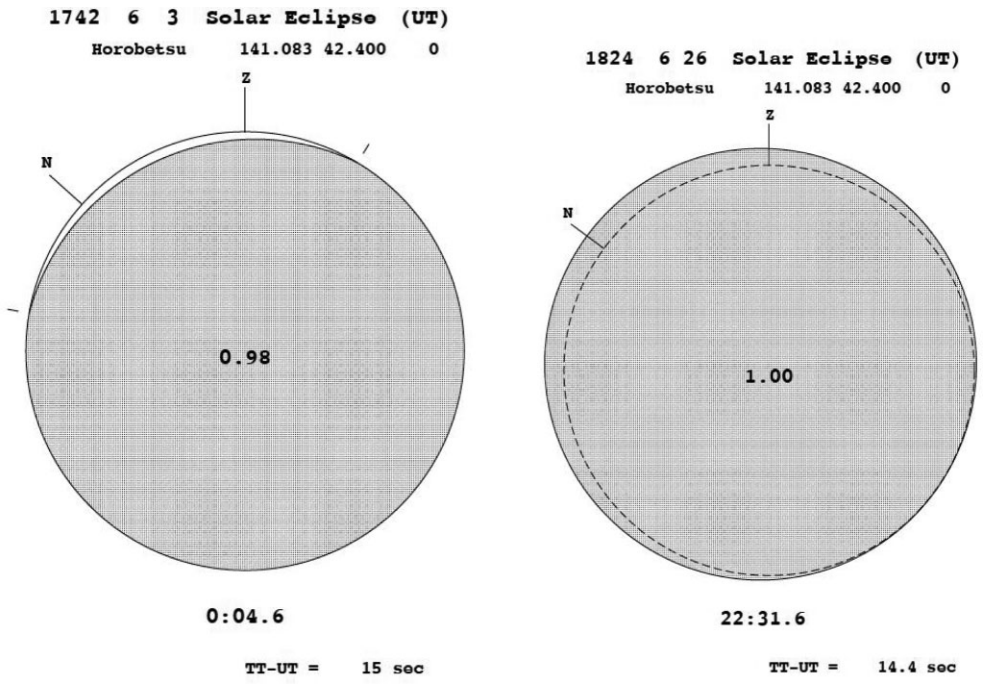

Fig. 10. Maximum eclipse magnitudes seen at Horobetsu on 1742 June 3 (left) and 1824 June 26 (right), which are almost identical to those seen at Moto Muroran because of the geographical proximity.

indicated that his residence was at Horobetsu from 1886 to 1891 (Batchelor 2008, pp. 212–235) and described a bear's funeral at Moto Muroran immediately before the eclipse report (Batchelor 2008, pp. 224–225). On this basis, it is reasonable to locate the observational site near Horobetsu (N42°24′, E141°05′) or Moto Muroran (N42°22′, E140°55′).

It is possible to narrow the chronology further, as total solar eclipses are rare and their totality paths are narrow. Batchelor's report described this event as a total

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Fig. 11. Trouvelot's drawing of the total solar eclipse on 1878 July 29 (courtesy of the New York Public Library; Plate III of Trouvelot 1882),[1] which took place slightly before the minimum of Solar Cycles 11/12 in 1878 December [table 2 of Hathaway (2015); figure 11 of Clette & Lefèvre (2016)].

solar eclipse, which occurred five generations ago. His folklore quote leaves little doubt about the total eclipse witness, mentioning the "black dead sun," the dark sky with bright stars, and abnormal animal reactions (see, e.g., Stephenson 1997). On this basis, we consider that this folklore eclipse is a total solar eclipse within the six generations including Batchelor's informant himself/herself. According to Von Oppolzer's eclipse atlas, only three total solar eclipses occurred near Hokkaido Island within three centuries before this eclipse, which were on 1636 August 1, 1742 June 3, and 1824 June 26 (Von Oppolzer 1887, Blatt 130–148).

Taking the state-of-the-art calculation of ΔT into account (Morrison et al. 2021), we have geographically visualised the totality paths (figure 9) and computed the magnitudes of these eclipses, as seen in Horobetsu (figure 10). Our calculation confirms that Horobetsu and Moto Muroran managed to see the only total solar eclipse in 1824 within three centuries before Batchelor's folklore account. Here, the first possibility (1636) is ruled out, because it is still difficult to consider that within the six generations (including the informant himself/herself) (see also, e.g., Ogawa & Yamada 1998), and the totality path significantly missed Horobetsu and Moto Muroran in this eclipse. As shown in figures 9 and 10, the 1824 eclipse included Horobetsu and Moto Muroran in its totality path and achieved a maximum magnitude of 1.00 at Horobetsu at 1824 June 26 $22^{h}31^{m}37^{s}$ UT ($07^{h}53^{m}28^{s}$ LAT on 1824 June 27) and at Moto Muroran at $22^{h}31^{m}27^{s}$ UT ($07^{h}52^{m}37^{s}$ LAT on 1824 June 27). In contrast, the 1742 eclipse did not locate these sites in its totality path and achieved a maximum magnitude of only 0.98 at Horobetsu at $00^{h}04^{m}36^{s}$ UT and at Moto Muroran at $00^{h}04^{m}22^{s}$ UT on 1742 June 3 (i.e., at $9^{h}31^{m}29^{s}$ LAT and $9^{h}30^{m}34^{s}$ LAT), on that date. It is known that solar disks can still cause retinal photochemical injury even with 99% obscuration (Littmann et al. 2008, pp. 166–168). Furthermore, to locate Horobetsu in the 1742 totality path, we would need to expect an unrealistically large short-term ΔT variation ($-1638\,\mathrm{s} < \Delta T < -386\,\mathrm{s}$), in contrast with the existing ΔT (15 ± 2 s) around 1742 (Stephenson et al. 2016; Morrison et al. 2021). Therefore, it is unrealistic to believe that the informant's ancestor saw this total eclipse, unless he travelled all the way to the south-eastern coast of Hokkaido Island.

With respect to the folklore about the 1824 eclipse, we need to emphasise the significance of the probable coronal description: "The black dead sun shot out tongues of fire and lightning from its sides, and the stars shone brightly" (Batchelor 1887, p. 228). The reported fiery tongue and lightning from the sides morphologically resemble the coronal structure around a solar eclipse near the solar minimum (figure 11). In fact, this total solar eclipse was chronologically located immediately after the minimum of solar cycles 6/7 in 1823 (figure 12). This probable coronal report, as such, provides a unique report of the solar coronal structure around the Dalton Minimum (about 1797–1827; see Usoskin 2017), similar to those reported for the total solar eclipse in 1806 June, which exhibited maximum-type solar coronal streamers (Hayakawa et al. 2020). These eclipse reports contrast the Dalton Minimum with the Maunder Minimum (Usoskin et al. 2015), for which coronal streamers were missing, according to reports based on visual observations (Eddy 1976; Riley et al. 2015; Hayakawa et al. 2021a).

6. Conclusion

In this study, we analysed two early accounts of solar eclipses seen in Hokkaido before Batchelor's eclipse observation in 1887 (Batchelor 1887) based on the latest ΔT value calculations (Morrison et al. 2021). The first account was recorded in Denkichi Abeya's eclipse report, cited in Tokunai Mogami's travel account (Ezo Soshi; figure 3, left), which was associated with the annular solar eclipse on 1786 January 30, and the earliest datable solar eclipse in Hokkaido (Sueoka 2009). Our analyses revealed that this eclipse was not a simple annular eclipse but rather a hybrid eclipse that appeared as an annular eclipse in the south-eastern sea of Hokkaido Island. The probable observational site was located at Mitsuishi and hence was outside the

[1] ⟨https://digitalcollections.nypl.org/items/510d47dd-e81f-a3d9-e040-e00a18064a99⟩.

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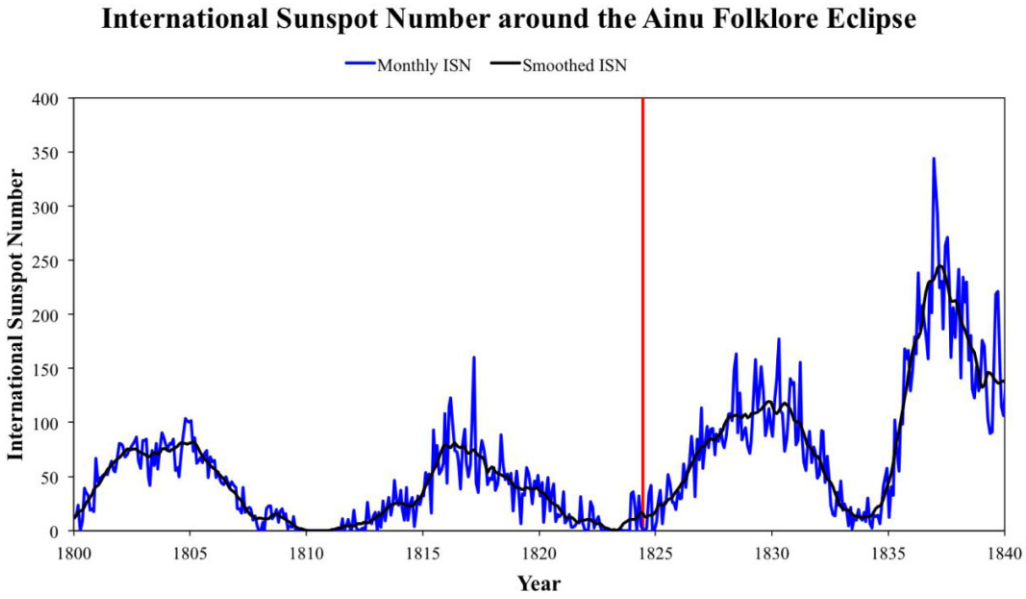

Fig. 12. Ainu folklore eclipse contextualised with respect to the international sunspot number. The black and blue curves represent monthly and smoothed monthly international sunspot numbers (Clette & Lefèvre 2016). The vertical red line indicates the timing of the Ainu folklore eclipse, as determined in this study.

annularity path (figure 4). Accordingly, Tokunai's description was probably not for an annular solar eclipse but rather for a deep partial solar eclipse, as the maximum eclipse magnitude reached only 0.96 at $03^{h}36^{m}02^{s}$ UT (figure 5, left). This eclipse was also witnessed in the Ryukyu Kingdom (figure 3, right), probably as a deep partial eclipse with a magnitude of 0.99 at $02^{h}51^{m}53^{s}$ UT (figure 5, right). These cases form unique reports of simultaneous eclipse observations from the Hokkaido and Okinawa Islands.

The second account was found in Kan'ichiro Mozume's eclipse record on 1872 June 6 (figure 6). To date, no records of that specific eclipse were known to the scientific community, though the annularity path went over Hokkaido Island. Further, Kan'ichiro Mozume evidently recorded an annular solar eclipse in his diary. His description is consistent with our astronomical calculation, which indicates an annular eclipse visibility of the maximum magnitude 0.97 at $13^{h}24^{m}33^{s}$ LAT at Otaru (figures 7 and 8). The reported timestamp seems consistent with our astronomical calculations, if we regard them as following the Kansei Calendar.

The third account was cited as ancestral folklore of a total solar eclipse, without explicit dates, by Batchelor (1887), who collected eclipse folklore from the local Ainus for his eclipse observation on 1887 August 19. We determined that the probable observational site was at either Horobetsu or Moto Muroran, as Batchelor probably collected this story in connection with his eclipse observation in 1887. We were able to associate this folklore eclipse account with the total eclipse that occurred on 1824 June 26, based on the calculated totality paths for six generations using the latest ΔT values (figures 9 and 10).

Our astronomical calculations have benefitted the reliability assessment for these historical documents and further managed to locate a legendary eclipse in Batchelor's Ainu folklore chronologically. Amongst them, Kan'ichiro Mozume's record is the only eyewitness account, whereas the other two are based on hearsay. For these eclipses, Tokunai Mogami placed his emphasis on the local reactions, while Kan'ichiro Mozume and John Batchelor placed their emphases on the celestial events. Interestingly, for the Ainu folklore eclipse, we found probable indications of visible coronal streamers in this account, including "tongues of fire and lightning from its sides" from the "dead black sun." This description resembles that of coronal streamers in solar minima (figure 11). This eclipse was situated around the Dalton Minimum (about 1797–1827; Usoskin 2017) and probably indicates the visibility of coronal streamers immediately after the minimum of solar cycles 6/7 in 1823 (figure 12). Therefore, while this eclipse report may further contrast the Dalton Minimum with the Maunder Minimum, it emphasises a similarity of the Dalton Minimum and modern solar cycles.

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